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THE USES OF POLYMERS IN CONCRETE: POTENTIALS AND DIFFICULTIES

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Abstract: This paper aims to understand and evaluate the potentials of using polymers in concrete for different construction applications. Initially, polymers will be defined from a chemical perspective and their general mechanical behavior is explained in order to provide an insight on the benefits of using polymers in concrete. Three types of polymer concrete, namely Polymer Concrete, Polymer-Impregnated Concrete and Polymer-Modified Concrete, are then thoroughly described to present their respective mechanical behaviors, advantages, disadvantages and possible applications. The challenges of using polymer concretes are then discussed as well as the possible future development and uses of such materials. This would allow engineers and policymakers to consider polymer composites as a sustainable construction material for different civil structures.

1 INTRODUCTION

Polymers are complicated large molecules composed primarily of repeating covalently bonded structural. Polymers are generally categorized on their thermal properties and can be grouped into thermoplastics, thermosets and elastomers. Polymers exhibit a large range of mechanical properties that tend to vary considerably with temperature.

The use of polymers in concrete was first tested in the 1950s when polymer concrete was used to produce building cladding. Polymer Concrete (PC) uses polymers as a substitute for Portland cement. Polymers are mixed with other concrete ingredients to produce a hard-plastic material. The second type of polymer concrete used was Polymer-Impregnated Concrete (PIC) which was developed in the 1960s. It consists of soaking a hardened Portland cement concrete member in a low viscosity monomer that will then penetrate the concrete and fill its pores once polymerized. The last kind of polymer concrete is called Polymer-Modified Concrete in which polymers are added to Portland cement concrete during the mixing stage to enhance its mechanical properties.

The use of polymers is currently limited because polymer concretes face a number of challenges. Polymers are relatively expensive materials and other more competitive construction materials are usually chosen over polymers (Dhir & Jackson, 1996). Another limiting factor is the damaging effect of heat on the molecular structure of polymers (Dhir & Jackson, 1996), which leads these large molecules to soften or melt when subjected to high temperatures.

2 POLYMER MATERIAL AND ITS CLASSIFICATION:

Polymers, as indicated by the Greek origin of the word “poly” meaning several and “mers” meaning parts), is a large molecule consisting of repeating structural units linked by covalent bonds (Ravve, 2012). These structural units can be connected in a great variety of ways which include the following: a) Linear polymer: simplest type of connection, linear polymers consist of external and internal units. Internal units are connected to each other and repeated “n” times while the external or terminal units are placed at the ends of the polymer; b) Branched polymer: fall under linear polymers but has a branch-like geometry; c) Network polymer: formed following the connection of branches from different polymers; d) Copolymer: molecule consisting of two or more structural units (i.e. Copolymers may display a linear or branched structure) and d) Block copolymer: copolymers composed of blocks of individual polymers.

Polymerization is a process that may happen in the three-dimensional space. When it does so, a phenomenon called gelation, which consists of mixture change from a viscous liquid state to an elastic gel state, may occur (Ravve, 2012). The creation of the gel is the physical representation of the cross-linking reactions that occur on a molecular level and that transform a ductile polymer solution into a soft solid gel.

Prior to reaching gelation, the polymer is soluble and fusible, but upon reaching gelation, the polymer loses its solubility and its fusibility (Ravve, 2012, Miller-Chou & Koenig, 2003). However, not all polymers reach gelation, thus creating a distinction between thermoplastics, which do not reach gelation, and thermosetting polymers, which reach gelation.Thermoplastic polymers are made of independent linear polymer chains which melt to form a liquid possessing a high viscosity. Since they do not gel, they can be melted or solidified by changing the temperature (melting occurs between 100 to 250°C (Ravve, 2012).

Thermosets, on the other hand, are highly cross-linked polymers that cannot be melted again once formed, since the internal parts of its structure are not able to move freely relative to each other due to gelation. The creation of gel is an important property to consider when dealing with thermosets since they cannot be re-melted afterward, meaning that the creation of whatever object or member containing the thermoset must occur prior to gelation.

There also exists a type of cross-linked polymers that only exhibit a slight degree of cross-linking. These polymers are known as elastomers since the light degree of cross-linking only prohibit large-scale chain movements (Ravve, 2012). Elastomers exhibit rubbery properties. A particular kind of elastomer, known as thermoplastic elastomers, is processed as a thermoplastic polymer but retains that rubbery behavior at normal temperatures.

3 POLYMER STRUCTURE AT THE SOLID STATE

Polymers possessing a simple and regular molecular structure tend to exhibit good packing in a solid state since they are able to have a regular alignment of their molecules by forming crystallite. This crystalline structure increases the density and the attractive forces between chains (Dhir & Jackson, 1996). Thus, polymers possessing some sort of a crystalline structure are usually used as fibers in civil engineering applications. Indeed, their strength, modulus of elasticity and stiffness can be increased by exposing them to elevated strains to arrange their molecular chains parallel to the axis fiber.

Certain linear thermoplastic polymers are made of randomly intertwined polymer chains (University of Illinois, 2017). At normal temperatures, these large molecules are stiff and brittle, but gain the ability to move under applied stresses as the temperature increases. Once the glass transition temperature is exceeded, these polymers become a viscous melt (Dhir & Jackson, 1996).

Thermosets and elastomers are also known to have an amorphous structure. However, it is important to note that while elastomers do have an amorphous structure when they are not subjected to any strain, their chains can align themselves to form a temporary crystalline structure under high strains (Dhir & Jackson, 1996).

4 POLYMERS IN CONCRETE

Polymers were first introduced into concrete in the 1950s when extensive research on polymers was being conducted. While the use of polymers in concrete was not widespread at first, the creation of Polymer Impregnated Concrete (PIC) in the 1970s contributed to increasing the use of polymers in concrete.

Polymer-modified concretes have since then received a lot of attention and have been used in many different areas such as structural repairs, machine tools, floor tiles, building cladding, tunnel lining, hazardous waste containment, laboratory floors, floors in shopping malls etc. Polymer-modified concretes have also recently been of interest to environmental engineering since the use of polymers makes polymer-modified concrete a sustainable material by saving natural resources, thus giving this type of concrete the potential to become an important player as efforts to use sustainable resources and building materials are increasing (Fowler, 1999).

4.1 Polymer-Impregnated Concrete (PIC)

Research on polymer impregnated concrete started in the 1960s. PIC is produced by partially or fully impregnating dry hardened hydrated Portland cement concrete with a low viscosity monomer. The goal of this method is to eliminate the free water normally contained inside the voids in concrete after moist curing by filling these voids with a polymer. Once the polymer is in the concrete and is being heated, a small concentration of reactive molecules will appear and start polymerization that will spread through all the pores and form a solid polymer, thus effectively filling the voids with polymer (Gambhir, 2008). The most commonly used polymer for PIC is a thermoplastic polymer called methyl methacrylate because it has a low viscosity and is readily absorbed in concrete (Gambhir, 2008). Other polymers commonly used in PIC are styrene, polyester, butyl acrylate, acrylonitrile and epoxies.

4.1.1 Properties of Polymer-Impregnated Concrete

PIC exhibits a compressive strength that is typically three to four times greater than that of conventional Portland Cement concrete (up to 140MPa) (Ausker & Horn, 1971). Moreover, its modulus of elasticity can be fifty to one hundred percent higher than that of normal Portland Cement concrete (**Table 1**) (Li, 2011). PIC also has excellent durability and low permeability which make it particularly resistant to freezing and thawing and chemical attacks. The differences in mechanical properties between non-impregnated concrete and PIC were highlighted by (Li, 2011).

Table 1: Properties of PIC and Non-Impregnated Concrete (Li, 2011)

	Non-impregnated Concrete	PIC
Compressive Strength (MPa)	37	125
Tensile Strength (Ma)	2.9	10
Flexural Strength (Ma)	5.1	16
E (GPa)	55	43

Examining the behavior of PIC and ordinary concrete when subjected to loads, it was observed that while ordinary concrete exhibits a non-linear stress/strain relationship, PIC shows a more linear relationship between stress and strain at least until approximately seventy five percent of the failure load is applied (Ausker & Horn, 1971). This more elastic behavior can be attributed to bond developed between the impregnating polymer, the cement and the aggregate particles.

4.1.2 Applications

Polymer Impregnated Concrete can be used in a variety of fields. It is mainly found in bridge decks, pipes (transport of aggressive fluids), floor tiles, building cladding, storage tank for seawater, tunnel liners, hazardous waste containment, post-tensioned beams and slabs etc. (Li, 2011)

Unfortunately, despite its many advantageous properties, PIC remains an extremely expensive material given the high cost of the polymers and the complicated and labor-intensive manufacturing process. Therefore, PIC is only manufactured by one company in Japan (Fowler, 1999).

4.2 Polymer Concrete (PC)

Polymer Concrete was first used in 1958 to make building cladding. It is typically a mixture of aggregates and polymer binder, which completely replaced Portland cement. The most widely used polymers in this type of concrete are polyester-styrene, acrylics and epoxies (Li, 2011).

PC is mainly used for repair works but faces fierce competition from other repair materials and also suffers from high costs and lack of familiarity with engineers and contractors (Fowler, 1999).

4.2.1 Properties of Polymer Concrete

Polymer Concrete is fast curing, can easily be molded and provides good bond between concrete and steel reinforcement. It also has a high tensile strength, low water absorption, good freeze/thaw resistance, high damping properties and low thermal conductivity (Li, 2011).

However, PC has a low modulus of elasticity, high creep, shrinks significantly and is very sensitive to temperature changes (Li, 2011).

Furthermore, the properties of PC are influenced by the amount and type of polymers used in the mix as well as the curing temperature. The impact of the curing temperature on the strength development in polymer concrete was studied by Building Research Institute of Japan (Ohama, Concrete-Polymer Composites - The Past, Present and Future, 2011) and the results are outlined in Table 2.

Table 2: PC Strength and Curing Temperature (Mehta & Monteiro, 2006)

Curing Temperature	Compressive Strength (MPa)
50 to 70˚C	140
20˚C	105

4.2.2 Uses of Polymer Concrete

By being easily moldable, fast curing and a vibration damper, PC is often seen as an efficient repair material (Li, 2011). However, multiple factors need to be carefully considered prior to using Polymer Concrete. Indeed, there is only a limited number of polymers that can be used for the repair of wet concrete and cured PC does not bond to conventional concrete (Li, 2011). Moreover, the service temperature must be carefully studied since high temperatures have a strong impact on the properties of PC (Li, 2011).

Its low permeability makes it in an ideal candidate for uses in hazardous waste containment, piping, sanitary products, industrial flooring and building cladding. PC can also be used in tunnel linings, highway concrete works and pre-cast and cast-in concrete.

PC is very suitable for repair works on highways since it meets the time constraints usually imposed on contractors for highway construction works. The repair area is usually only closed for a few hours to minimize traffic disruption and materials like PC that are fast curing and quickly develop high strength are usually used. But the fast curing of PC also means that the working time for this type of concrete is relatively short and must be studied when planning concrete placing and finishing (Li, 2011).

4.3 Polymer-Modified Concrete (PMC)

Polymer-Modified Concrete adds polymers into Portland cement concrete during the mixing stage to strength the cement hydrate binder. Very few polymers can be used in PMC, but there are five types of polymeric modifiers that are commonly used: polymer dispersions (i.e. Latex), re-dispersible polymer powders, water soluble polymers, liquid resins and monomers (Li, 2011).

4.3.1 Properties of Polymer-Modified Concrete

Adding polymer modifiers to concrete has several impacts on the properties of concrete. One of the main impacts of these modifiers is the reduction of the water/cement ratio and the resulting increase in concrete workability.

The presence of polymers in concrete reduces the amount of water lost during the hydration process and therefore decreases the initial volume of water needed in the concrete mix (Lewis & Lewis, 1990). Polymers were also found to have a lubricating effect on the properties of wet concrete and therefore contribute to increasing concrete workability while allowing for a reduction in water/cement ratio (Lewis & Lewis, 1990). The compressive strength of polymer-modified concrete is less than that of conventional concrete.

Polymer modification of concrete helps reduce the amount of water movement within concrete by having the polymer fill pores in concrete thus preventing water from freely moving within the concrete structure (American Concrete Institute Committee 548, 2003). Polymers also fill micro-cracks present in concrete and limit their spread (American Concrete Institute Committee 548, 2003).

Careful attention must be paid to the amount of polymers added to concrete since an excess of polymer may damage concrete by causing air entrainment and by leading the PMC to behave more like a polymer (American Concrete Institute Committee 548, 2003). A deficit in polymers also has a negative effect on concrete since it decreases the water reducing properties of the polymer and does not allow for the improvements of mechanical properties one would expect when doing polymer modification (American Concrete Institute Committee 548, 2003). The optimum amount of polymer that should be added has been estimated to be between 7.5 to 20% of dry polymer solids by mass of cement (American Concrete Institute Committee 548, 2003). Table 3 presents the major polymers used in PMC.

Table 3: Polymers Used in PMC (American Concrete Institute Committee 548, 2003)

Major Polymers
Acrylic Polymers
Copolymers
Styrene Acrylic Copolymers
Styrene Butadiene Copolymers
Vinyl Acetate Copolymers
Vinyl Acetate Homopolymers

4.3.2 Applications of Polymer-Modified Concrete

Polymer-Modified Concrete is mostly used as a repair material on highways and bridges. Traffic conditions on highways and bridges are usually such that access to the highway or bridge should not be cut off for too long to minimize traffic disruption. Thus, construction jobs in such environments tend to have significant time constraints. The fast hardening property of PMC makes it an ideal candidate as a repair material since its quick hardening means the required repair job can be completed within a tight schedule (Li, 2011). PMC may also be used in tunnels, swimming pool, high strength precast products, coatings for various surfaces and ceramic tiles adhesive.

5 COMPARISON BETWEEN CONVENTIONAL CONCRETE AND VARIOUS TYPES OF POLYMER CONCRETES

This section aims to highlight the main differences between the properties of conventional concrete, i.e. one that does not use polymers, and various types of polymer concretes. Overall, polymer concretes are found to possess higher compressive, tensile and flexural strengths than conventional concrete. Moreover, strength develops much faster in polymer concretes than in conventional concrete.

6 FUTURE DEVELOPMENT AND USES OF POLYMER CONCRETES

Concrete containing polymers are widely used as a repair material in the construction industry. They possess many advantageous characteristics such as high strength, excellent durability, low permeability, excellent freeze/thaw resistance etc. which make them usable in a wide variety of applications from repairing concrete bridges to the construction of hazardous waste containers.

However, the use of polymer concrete is limited by several factors, ranging from undesirable physical properties to high cost. Indeed, polymers in general are not suitable for use in places exposed to high temperatures since they tend to soften significantly under high heat. This makes polymers hard to use in building construction. Moreover, polymers are relatively expensive compared to other materials currently available.

Polymer concretes might see their use increase significantly in the coming years as efforts are now being made to preserve the environment and its limited resources (Fowler, 1999). Polymer concretes are therefore seen as sustainable construction materials since they increase the durability of structures when used as a repair material and help save natural resources.

7 SUMMARY

The use of polymers in concrete is a field that has been heavily researched since the 1950s. Polymers can be categorized into three main groups, namely: thermosets, thermoplastics and elastomers. Each type of polymer has its own set of mechanical properties that help civil engineers understand in which applications are suitable for a specific group of polymers.

There exist three types of concretes that use polymers. The first type of polymer is Polymer-Impregnated Concrete (PIC). PIC was developed in the 1960s and is produced by impregnating a concrete member with a low viscosity monomer which is then polymerized in-situ by heating or radiation. PIC has many advantageous characteristics such as excellent compressive strength, excellent durability and resistance to chemicals. However, it remains an extremely expensive material due to the complicated manufacturing process required to produce PIC. As a result of this, its use is relatively limited and there is only one company in the world that produces Polymer-Impregnated Concrete.

The second type of polymer concrete is called Polymer Concrete (PC). It was first used in 1958 and has a special composition since polymers are used to completely replace Portland cement. Polymers, hardeners, catalysts and admixtures are therefore mixed with aggregates to produce a hard material with aggregate as a filler. PC is usually used as a repair material for concrete structure thanks to its mechanical properties. It is known for curing rapidly, its high damping properties, its high strength and excellent durability. However, its high cost and lack of presence on the market make its use relatively limited.

The third type of polymer concrete is Polymer-Modified Concrete (PMC). In this case, polymers are simply added to regular Portland cement concrete during the mixing stage to enhance its strength and other mechanical properties. Very few polymers can be added to concrete since most would yield poor results. The five main types of polymers used in PMC are polymer dispersions such as latex, monomers, liquid resins, redispersible polymer powders and water-soluble polymers. The most advantageous properties of PMC are, amongst others, high strength, low permeability and excellent bond to concrete.

Polymer concretes are mostly used in repair jobs in the construction industry but may also be used in architectural moldings, tunnels, laboratory floors, hazardous waste/chemical containment, adhesive for ceramic tiles etc. Despite their numerous qualities, the use of polymer concretes is limited by the relative high cost of polymers compared to other repair materials, the lack of familiarity of contractors and engineers and the poor fire resistance of polymers. The last property is one of the main reasons why the use of polymers is limited. When subjected to relatively low temperatures, the molecular structure of polymers is damaged and they tend to soften or melt. The benefit of using polymers in concrete is then quickly lost.

Polymers may become more widely used in concrete over the coming years since polymer concretes are generally regarded as sustainable materials as they increase the longevity of existing concrete structures when used as a repair material and are resources saving. These characteristics match that of the construction materials sought in the construction industry at the moment since considerable efforts to preserve the environment and its resources have been made recently.

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